Forest Policy and Economics 163 (2024) 103204

Contents lists available at ScienceDirect

Forest Policy and Economics

journal homepage: www.elsevier.com/locate/forpol

Synergies and trade-offs in the European forest bioeconomy research: State of the art and the way forward

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ARTICLE INFO

Keywords:
Biodiversity
Circular bioeconomy
Climate change
Ecosystem services
Foresight
Forest research gaps
Sustainability transition
Wood production

ABSTRACT

The management and governance of forests must consider the synergies and trade-offs between different societal goals, especially with the bioeconomy being a key factor in recent sectoral strategies worldwide. This literature review explores the multidimensional concept of synergies and trade-offs, focusing on scientific publications dealing with the European forest bioeconomy. The objectives are twofold: 1) to provide an overview of the reviewed literature, including publication outlets, disciplinary diversity, and geographic scope of the studies; and 2) to analyze the synergies and trade-offs assessed by the reviewed articles, including the temporal scope of the assessment, the value chain segment considered, the methods used, and the policy implications and research gaps identified. The results show that European forest bioeconomy research concentrates on Finland, Sweden, and Germany, the three largest roundwood producers in the EU. The research is highly multidisciplinary (with a strong presence of social sciences), employing a variety of qualitative and quantitative methods. Out of the 138 studies reviewed, 22% explicitly analyze synergies and/or trade-offs in the forest bioeconomy. The reported synergies were widely varied, while most commonly reported trade-offs related to wood production versus climate change mitigation, biodiversity, and more generally other ecosystem services. The use of the synergy and trade-off concepts is often inexact, and the policy implications articulated in the literature are frequently formulated in generic terms, emphasizing communication. The findings and recommendations of this review are thus of relevance for both the scientific and practitioner/policy community.

1. Introduction

The New EU Forest Strategy for 2030 (European Commission, 2021) and the EU Bioeconomy Strategy (European Commission, 2018) place a strong emphasis on the role of forests in achieving EU sustainability objectives, as well as global ambitions set by the Sustainable Development Goals (SDGs), the Paris Agreement and the Kunming-Montreal Global Biodiversity Framework. The EU Bioeconomy Strategy suggests that bio-based products can replace fossil-based counterparts. This may contribute to climate change mitigation, generate incomes and jobs, and support rural development and sectoral renewal.

However, scholars point out that various EU Strategies have failed to fully recognize and address the incoherences and trade-offs of managing natural and semi-natural ecosystems, including forests, to meet multiple societal goals (Aggestam and Pülzl, 2018; Beland Lindahl et al., 2023; Köhl et al., 2021; Moosmann et al., 2020; Muscat et al., 2021; Winkel et al., 2022). For example, according to Beland Lindahl et al. (2023) research shows that European forests face increasing and partly competing societal demands, a trend which is accelerated by a politically promoted shift towards the bioeconomy.

The bioeconomy concept became widely popular after the release of the Organisation for Economic Co-operation and Development (OECD) Bioeconomy report in 2009 (OECD, 2009), followed by the first EU Bioeconomy Strategy in 2012 (European Commission, 2012). Since then, several scientific fields have tackled the concept, providing valuable insights into its technical, conceptual, and policy development. Some of the earlier forest-related studies include Staffas et al. (2013), Hetemäki (2014), and Ollikainen (2014). The conceptualization of the bioeconomy in general, as well as the forest bioeconomy, has evolved. It was originally focused on developing innovative products and biotechnologies with little emphasis on the sustainability of production systems. More recently, it has expanded to consider sustainability issues

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https://doi.org/10.1016/j.forpol.2024.103204
Received 6 December 2023; Received in revised form 15 February 2024; Accepted 19 March 2024
Available online 3 April 2024

related to biomass sourcing, as well as to include the value of immaterial ecosystem services. As Hetemäki et al. (2017), the European Commission (2018), and Palahí et al. (2020) stress, in principle the forest bioeconomy should include the value creation related to all the forest ecosystem services, such as economic and social opportunities related to non-wood forest products and services, tourism, and recreation, water supply and purification, and carbon sequestration.

Bioeconomy is also understood differently by different actor groups (Hodge et al., 2017), and thus remains a flexible concept (Pülzl et al., 2014). Over the years, several bioeconomy conceptual approaches have appeared in the scientific literature. Bugge et al. (2016) make the useful distinction between biotechnology, bio-ecology, and bio-resource research visions. The bioeconomy has been picked up by the forest-research community as well. For example, Piplani and Smith-Hall (2021) distinguish five schools of thought in the forest-bioeconomy: the biotechnology, techno-bioresource, socio-bioresource, eco-efficiency, and eco-society. International organizations like the EU and the OECD, as well as various national bioeconomy strategies, promote a normative view of the bioeconomy concept, usually framed as a means to achieve various economic and societal goals. This perspective is also taken by forest sciences dealing with the bioeconomy concept through the lens of existing bioeconomy policies (Holmgren et al., 2020).

First, the bioeconomy is seen to contribute to the need to move away from the prevailing fossil-based economy, which is based on the use of fossil resource deposits such as coal, oil, and natural gas. The idea of forest bioeconomy is that various human needs and desires can be fulfilled by sustainable utilization of renewable and sustainably managed forest resources, instead of non-renewable fossil resources, even if not totally. The second essential part of the forest bioeconomy is to innovate and bring new, more resource-efficient, circular, and environmentally friendly forest-based products into markets. Thus, the forest bioeconomy seeks to produce the traditional products more resource-efficiently and fossil-free, as well as extend these to a wide range of new products, such as bio-based chemicals and engineered wood products.

The expectations placed on European forests, such as promoting forest-based products, rural development, and scientific and industrial innovation, all the while addressing climate change and biodiversity loss, are all pressing issues acknowledged by policymakers and citizens alike. However, although forest resources are renewable, they are still limited. Policies take these objectives as given, although one can question how well the forest bioeconomy can deliver on all the above-mentioned objectives. Policy documents often tend to ignore the complexity of achieving multiple, and at times, conflicting goals (Schulz et al., 2022). Therefore, the discussion on how we use forest resources and for what purpose is an important one in Europe. Given this context, it is important to seek to strategically maximize synergies and minimize trade-offs between the different usages of forests (Biber et al., 2020; Deng et al., 2023; Hetemäki et al., 2022; Hetemäki et al., 2017; Howe et al., 2014).

In the classical application of the concepts of synergies and trade-offs in economics, synergies may refer to the positive interactions or effects that occur when two or more economic factors create a greater outcome than the sum of their individual contributions. In sociology, synergies and trade-offs are concepts used to analyze the interactions and choices within social systems and structures. In forest sciences, studies investigating synergies and trade-offs have sought to understand the interrelationships between divirgent forest management objectives, ecological processes, and societal demands (e.g., Beland Lindahl et al., 2023; Winkel et al., 2022). The literature shows that there are numerous ways forest management measures could potentially enhance synergies and minimize trade-offs between the forest ecosystem services or different ways of using forests (Pan et al., 2022).

Against this backdrop of different competing societal demands from forests, it is paramount to understand the potential synergies and conflicts in the forest-based bioeconomy. The overarching goal of this review paper is to understand how the scientific literature on the forest bioeconomy addresses synergies and trade-offs related to ecosystem services (e.g. biodiversity, climate, wood) or other sustainability/societal issues (e.g. rural development, resource efficiency). More specifically, we set out the following objectives: (1) to provide an overview of the forest bioeconomy literature, in terms of publishing outlets, disciplines, and geographical scope, and tge extent to which it addresses the synergies and trade-offs with forest ecosystem services; (2) to review in detail the articles that provide empirical evidence of synergies and trade-offs in the forest bioeconomy by addressing the questions: What is the temporal scope of the analysis? Which parts of the value chain are considered? Which methods are used? What synergies/trade-offs are analyzed and found? What are the policy implications and research gaps discussed?

2. Conceptual background on synergies and trade-offs

Synergies and trade-offs have been addressed in different disciplines and contexts. The terms “synergy” or “trade-offs” are often used in a loose and context-dependent manner across various academic disciplines and studies. Their specific meanings can vary significantly based on the field of study. Even within a particular discipline, their interpretation may differ. For example, in the economic and business disciplines, synergies and trade-offs typically refer to the allocation of resources among competing economic priorities (Angus-Leppan et al., 2010), whereas in sociology or political science, the terms often describe collaborative efforts or partnerships between stakeholder groups that can lead to better or worse outcomes between government agencies, nonprofit organizations or stakeholder groups that collaborate to achieve synergistic effects in addressing different issues (e.g., Nilsson and Weitz, 2019; Timko et al., 2018).

In ecosystem services research, trade-offs are described as the conflicts occurring when efforts aimed at increasing the quantity or quality of certain service(s) may result in the decrease of others in space and time (Vallet et al., 2018). Synergies are the opposite of this. For example, maximizing provisioning services through the intensified management of forests for timber production, could reduce biodiversity levels and thus diminish the availability of regulating (e.g., water, climate, soil regulation) and cultural services (e.g., nature-based recreation, local and indigenous values), while typically more synergies are found between regulating and cultural services (Braat and Groot, 2012; Howe et al., 2014).

In economics, a concept often used to illustrate and study trade-offs and synergies between ecosystem services is the production possibility frontier (PPF). Behind the PPF is a production function that describes what is possible in transforming resources into ecosystem services (Vallet et al., 2018). Consumer theory is the basis of indifference curves (IC), which are derived from utility functions that measure the contribution of ecosystem services to an individual or group’s well-being. Thus, the PPF and IC approach can be used to study both the trade-offs and synergies between ecosystem services as such, but also the synergies and trade-offs between the different individuals or stakeholders concerning the ecosystem services (Cavender-Bares et al., 2015; Chen et al., 2016; Vallet et al., 2018). Combining the PPF with the ICs of stakeholders (or individuals) defines the “utility possibility frontier” showing maximum achievable welfare combinations for the two stakeholder groups.

In the literature, many methods have been used to study synergies and trade-offs between ecosystem services, including monetary valuation methods, biophysical models, optimization programming methods, and multi-objective optimization methods (Chen et al., 2016). In empirical studies the trade-offs or synergies are often classified according to simple correlation analysis, a positive correlation between two ecosystem services (or two groups of services) is classified as synergy, and a negative one as a trade-off. This approach implicitly assumes that correlation also implies causality, which is not necessarily the case (Ronzon, 2023; Vallet et al., 2018).

The analysis of synergies and trade-offs has also been applied to the analysis of the relationships between sustainable development goals (SDGs), adopted by the United Nations in 2015. In that context, synergies are achievements on one goal that contribute toprogress towards other goals; trade-offs occur when progress towards one goal produces detrimental effects to other goals (Breuer et al., 2019; Renaud et al., 2022; Ronzon, 2023). A similar approach has been adopted to study the policy interlinkages between the multiple objectives of the bioeconomy strategy and the SDGs (Ronzon and Sanjuán, 2020). Although several studies have attempted to draw global conclusions regarding synergies and trade-offs between sustainable development goals, they also highlight how such interactions change in space and time, and suggest that they may be causally affected by, e.g., better policies or technological and social innovations (Kroll et al., 2019; Pradhan, 2019).

Both in the context of ecosystem services and SDG literature, the goal of assessing and quantifying synergies and trade-offs is to help find policies and measures that minimize trade-offs and maximize synergies, thus enhancing progress towards a set of societal goals (e.g. a more sustainable ecosystem management, a more sustainable society). Moreover, it is also used to assess the divergences in stakeholders' values for the ecosystem services in question (King et al., 2015).

This study adopts a definition for synergies and trade-offs shared by most disciplines. Given two items A and B, a synergy represents a positive relationship between these items, and a trade-off represents a negative relationship. Items A and B could also be bundles of items, merged and aggregated into a homogenous category or index (Kroll et al., 2019; Vallet et al., 2018). Moreover, synergies and trade-offs are generally not universal or fixed in time and space, but rather tend to be affected by contextual factors, scale, and management/policy interventions.

3. Methodology

3.1. Literature search and definition of the sample

The use of semi-systematic literature reviews is well-established and is a useful approach to mapping themes and trends of complex topics that have been conceptualized and studied within different disciplines and research lines (Snyder, 2019). The review consisted of three steps, following the PRISMA process (Moher et al., 2009) of identifying and analyzing relevant literature (Fig. 1). We performed a search using Scopus and Web of Science and focusing on English language publications dealing with the forest bioeconomy published between 2012 and 2022. The year 2012 was selected because it was the same year that the first EU Bioeconomy Strategy was launched, and the concept of bioeconomy started to be more known and an object for an increasing number of studies.

The following Boolean search query was used: TITLE-ABS-KEY (forest* OR wood*) AND TITLE-ABS-KEY(bioeconom* OR bio-based). Initially, 158 studies were left in the sample after removing duplicate records. In the second step, only peer-reviewed articles dealing with the forest bioeconomy in Europe written in English were included for further analysis based on the abstracts. This screening resulted in a sample of 138 studies, which were considered for the review. In the final step, the remaining studies were divided between the four authors for the analysis.

3.2. Analysis

An analytical framework was developed for the review process based on the objectives of this study and the conceptual background given in Section 2. In the first step, from reading the full text of all articles included in the final sample ($n = 138$), we extracted the information regarding the publishing outlet, the main discipline of the study (e.g. economics, forest management, policy), and the geographical focus of the study (Europe; EU; country groups; national). In the second step, we screened the full text of the articles to determine whether the study included empirical evidence on synergies and trade-offs. We found that out of the 138 studies, 30 articles contained this type of information. For these studies, we extracted information about the temporal scope of the analysis (ex-post or present; future projection; foresight analysis), the value-chain coverage of the study (only forests; only markets; both forests and markets), variables assessed in the study, synergies and trade-offs found in the study, the method(s) used in the study, and the policy implications and research gaps highlighted by the study.

Synergies and trade-offs were summarized in two separate analyses. First, the studies were screened for all factors analyzed (from the methods and objectives of the studies) to get an understanding of the indicators covered. Second, the synergies and trade-offs found (from the results of the studies) were listed separately one pair of indicators at a time. For the analysis, the indicators were first listed verbatim. Due to the diversity of the approaches and levels of detail and the slightly different terminologies used, the names of the indicators were then harmonized to the extent possible to allow comparisons and summaries. Finally, they were grouped into broader categories based on the similarity of the items. While the process was systematic, it may not be entirely repeatable due to the heterogeneity of the primary data and the lack of a common unified framework as a basis. Thus, the categorization ought to be considered indicative only to serve the identification of knowledge gaps. Rather than providing exact numbers or meta-analyses of the results, the main aim of the review was to characterize the literature and the policy implications. The categorization and the related references are documented in Supplementary information 1.

4. Results

4.1. Forest bioeconomy literature: an overview

In terms of *publishing outlets,* the 138 studies reviewed were published in 62 different journals (Fig. 2). Overall, almost half (46%) of the studies in the sample were published in traditionally popular forest science-related journals, i.e. *Forest Policy and Economics*, *Forests*, *Sustainability*, *Journal of Cleaner Production,* and *Scandinavian Journal of Forest Research*. The remaining 65 studies in the "other" category were

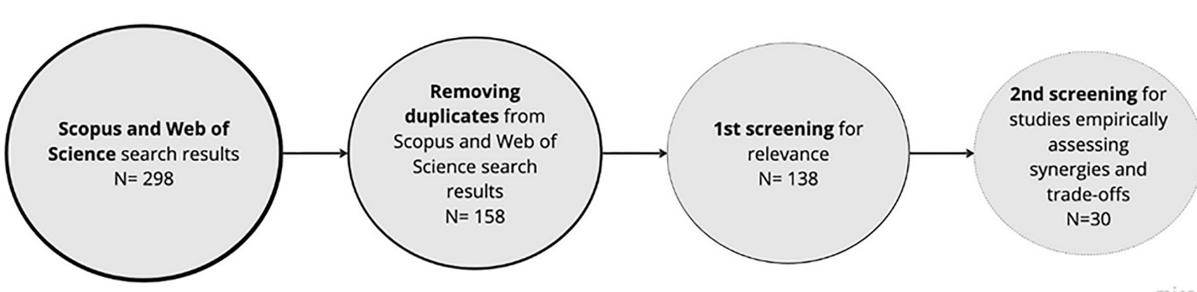

Fig. 1. Identification of documents for the review.

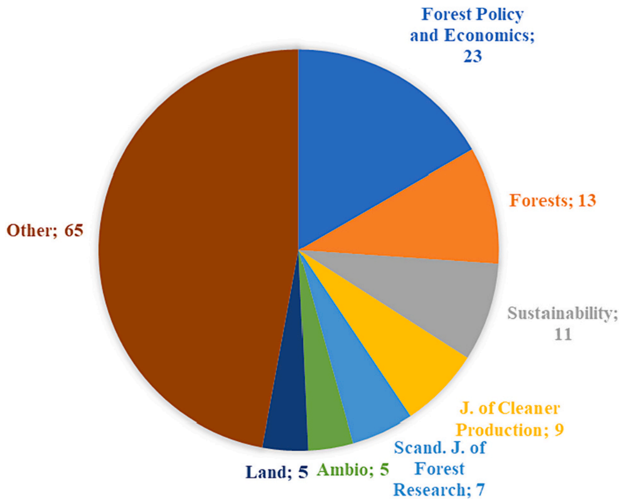

Fig. 2. Publishing outlets of the reviewed studies (N = 138). The numbers refer to the numbers of studies falling under each category.

allocated among 54 journals, none of which had more than 3 studies published. For example, the *Canadian Journal of Forest Research*, *Forest Science*, *International Forestry Review*, and *Journal of Forest Economics* published two or fewer studies during 2012–2022.

In terms of the *geographical scope*, 36 studies focused on Europe or the EU, while 74 studies focused on a single country (Fig. 3). These values exclude studies that analyzed country groups, in which Finland was part of 10 studies, Sweden in 7 studies, and Germany in 5 studies.

In terms of *the disciplines* of the studies, *policy and governance* dominated with 48 studies (Fig. 4). Following the typology suggested by Böcher and colleagues, these studies can be further classified into two subcategories of social and political science-related bioeconomy research (Böcher et al., 2020). Accordingly, we grouped the reviewed studies as follows:

(i) Studies dealing with governance questions, mainly focusing on technical or management questions on how to establish the bioeconomy and unleash its economic or ecological potential (e.g., Aggestam and Giurca, 2022; Gawel et al., 2018; Hagemann et al., 2016; Purkus and Lüdtke, 2020; Sanz-Hernández, 2021; Schulz et al., 2022).
(ii) Studies dealing with actor networks, power structures, and actor coalitions, beliefs or interests in the bioeconomy (e.g., Arnould et al., 2022; Giurca, 2020; Hafner et al., 2020; Korhonen et al., 2018; Ranacher et al., 2020a; Ranacher et al., 2020b).
(iii) Studies taking a more critical discursive approach to question the bioeconomy's potential to deliver on the proposed "green growth", equity, and inclusiveness (e.g., Fischer et al., 2020; Giurca and Befort, 2023; Kröger and Raitio, 2017; Mustalahti, 2018).
(iv) Literature dealing with political bioeconomy strategies in different world regions or national states (e.g., Pelli et al., 2017; Purwestri et al., 2020).

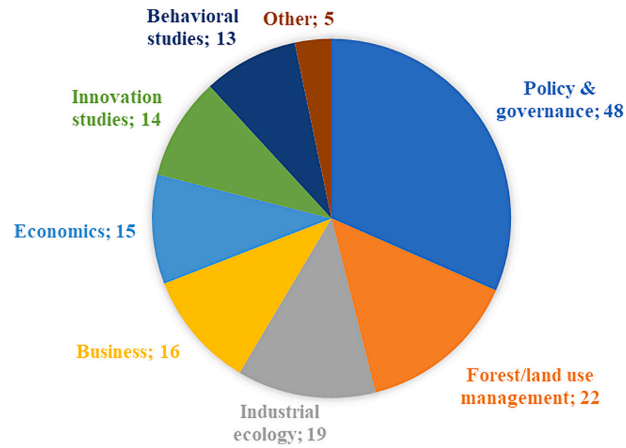

Fig. 4. Disciplines of the reviewed studies (N = 138). The numbers refer to the amounts of studies falling under each category.

Studies categorized under the discipline 'economics' dealt with the macro-economic analyses in the context of the forest bioeconomy (e.g., markets, gross domestic product, employment) (e.g., Kallio, 2021; Kalogiannidis et al., 2022; Lehtonen and Okkonen, 2013). Business studies dealt with, among others, corporate sustainability (e.g., Pätäri et al., 2017; Toppinen et al., 2019), business management practices (e.g., D'Amato et al., 2020; Morales and Dahlström, 2023; Näyhä, 2020; Näyhä, 2019), and servitization of the forest bioeconomy at the company or industry level (e.g., Pelli and Lähtinen, 2020).

The next biggest discipline representation was *forest management or land-use management* disciplines, with 22 studies. These studies are typically analyses of land-use policies or forest management measures and practices (e.g., clear-cut vs. continuous cover forestry) impacts on synergies and trade-offs between different forest ecosystem services, and

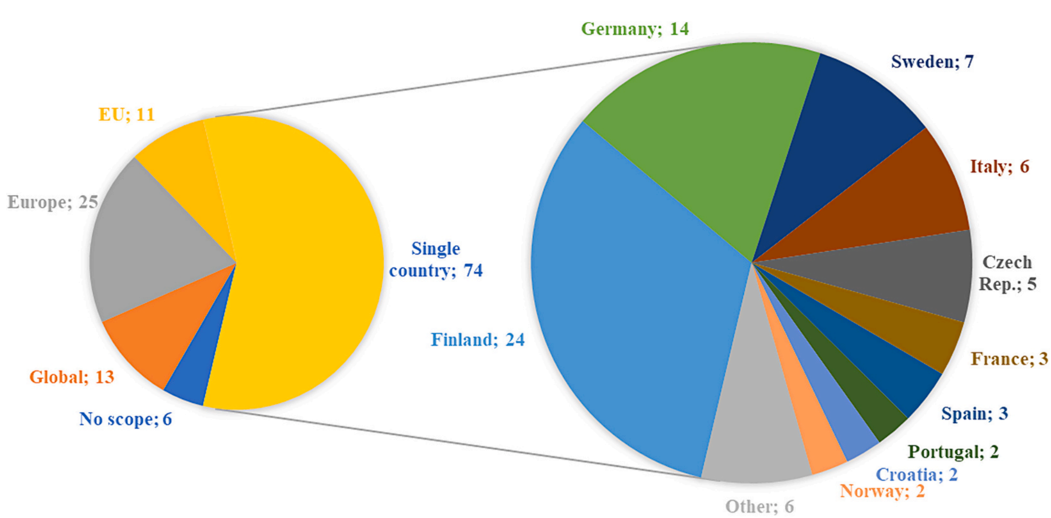

Fig. 3. Geographical scope of the reviewed studies (N = 138). The numbers refer to the amounts of studies falling under each category.

monitoring of progress towards sustainable bioeconomy, as well as that of actors co-governing the shift towards a forest bioeconomy. Also rather popular were studies labeled as *industrial ecology* with 19 studies. These included studies, e.g., on life cycle analysis and material flows, and the sustainability of value chains in the forest bioeconomy. Out of the 138 studies, 31 were based on economics and business disciplines. Studies categorized under the discipline 'economics' dealt with the macro-economic analyses in the context of the forest bioeconomy (e.g., markets, gross domestic product, employment) (e.g., Artene et al., 2022).

Innovation studies, representing 14% of our reviewed documents, included those dealing with the emergence of social or technological innovations in the forest bioeconomy (e.g., Ludvig et al., 2019). Finally, behavioral studies, dealing with stakeholder perceptions (e.g. students, citizens) and values of the bioeconomy, represented 13% (e.g., Navrátilová et al., 2021).

4.2. Synergies and trade-offs in forest bioeconomy literature

4.2.1. Synergies and trade-offs assessed and found in the literature

Out of the 138 studies reviewed, 30 studies (22%) provided empirical evidence of synergies and trade-offs. An explicit or primary objective to analyze synergies and/or trade-offs was found in 17 studies (12%). The synergies and trade-offs analyzed in the studies were highly diverse covering a wide range of topics and in varying detail.

Fig. 5 shows the number of occurrences of forest ecosystem services related indicator types or factors considered in the analyses divided into broad categories. One can observe that the dominating factors considered in the analyses have been wood production (16), carbon sink (11), and biodiversity (9). The regulating and cultural ecosystem services of forests have received less attention, though they were not absent. Economic and environmental aspects seem to have received the same amount of attention, while social and cultural factors have received considerably less. Further analysis revealed no changes in the popularity of the categories over time.

Out of the 30 studies providing empirical evidence of synergies and trade-offs, 16 found both synergies and trade-offs, 12 found only trade-offs, and 2 studies found only synergies. Compared to the trade-offs, the synergies found in the studies were highly dispersed and difficult to compare against one another. These included bilberry coverage and recreation opportunities (Vergarechea et al., 2023) as well as the joint biomass supply for sawmilling and biorefineries (Jonsson et al., 2021) and wood-based textile fibers and solid wood products (Kallio, 2021).

Following the number of factors considered, the trade-offs found in the studies were dominated by wood production versus climate change mitigation, biodiversity, and more generally other ecosystem services (Fig. 6). Of all the trade-offs found, in 64% of the studies, these trade-offs involved wood production as one of the two indicators observed. They were also highly varied and included, e.g., satisfying human needs with virgin wood fiber vs biotechnological production (Hafner et al., 2020), and land use for forests versus windmills and other sustainable infrastructure (Schulz et al., 2022).

The studies also covered measures for reducing the trade-offs, i.e., management interventions influencing the production possibility frontier between, e.g., wood production and biodiversity or water protection (e.g., Biber et al., 2020). Besides alternative management options in production forests, some studies compared the influence of natural climate solutions against bioeconomy targets suggesting mainly synergies for the former and trade-offs for the latter (e.g., Mazziotta et al., 2022). However, as forests cater to several needs simultaneously, a combination of tailored forest management measures is crucial in

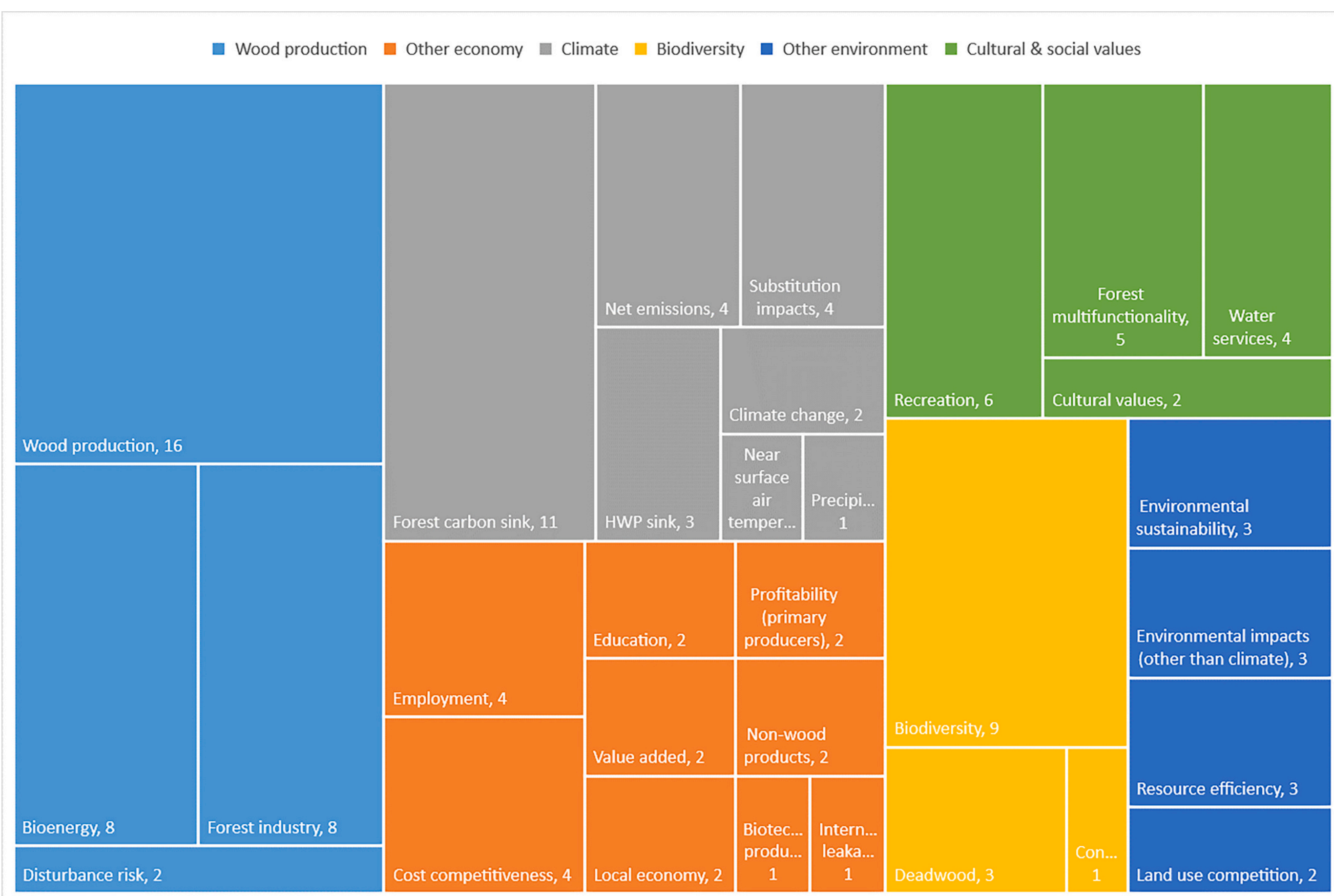

Fig. 5. Factors considered in the studies analyzing synergies and trade-offs (N = 30). The numbers refer to the number of occurrences in each category.

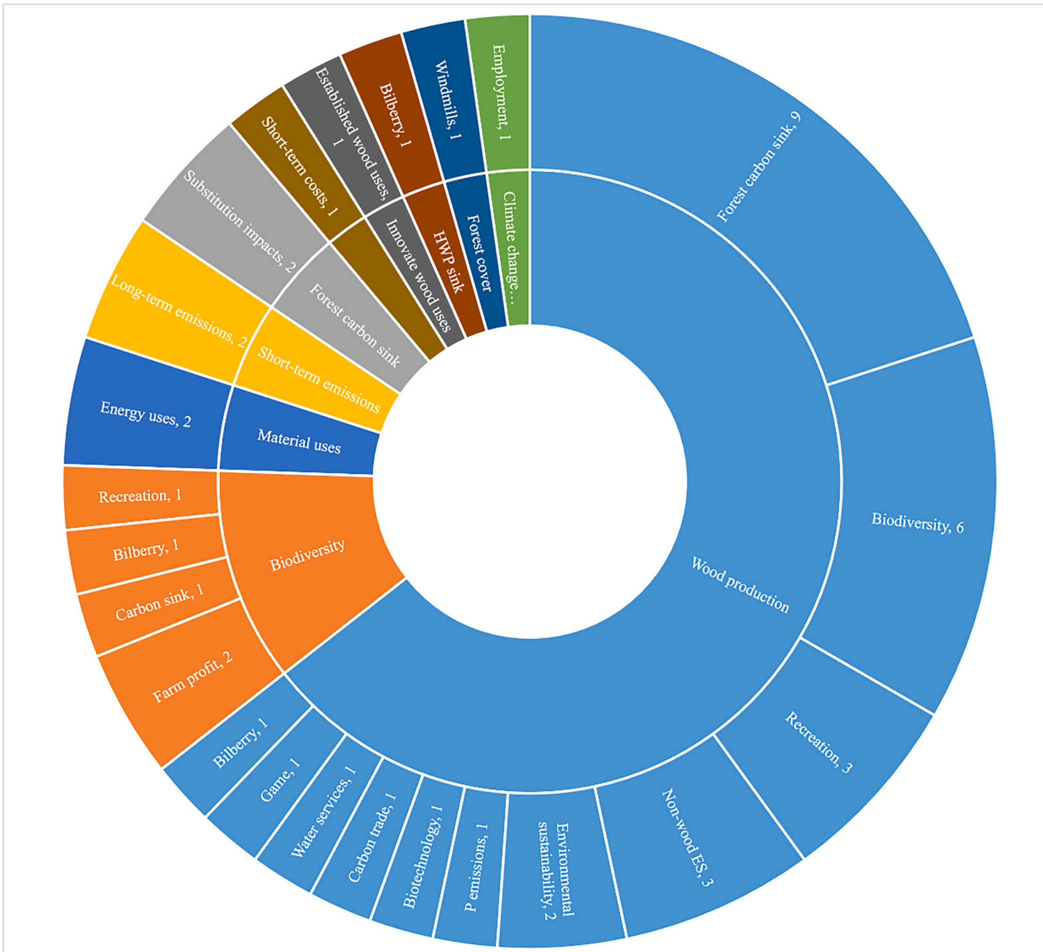

Fig. 6. Trade-offs found in the studies analyzing synergies and trade-offs (N = 30). The numbers refer to the number of occurrences in each category. For example, a trade-off between wood production and forest carbon sinks has been identified in nine studies.

minimizing the ecological and socio-cultural costs of commercial forest management (Eyvindson et al., 2018; Vergarechea et al., 2023).

4.2.2. *Methods and scope of the reviewed literature*

The 30 studies providing empirical evidence of synergies and trade-offs used a range of methodological techniques and displayed various levels of detail in the analysis (Fig. 7). For example, some studies employed quantitative measures, such as Pearson correlations, to model the response of indicators to certain management regimes (e.g., Vergarechea et al., 2023), while others relied on qualitative content analysis to explore competition between ecologist vs. biomass industry views (e.g., Sanz-Hernández et al., 2020). Clearly, the most common method of analysis has been forest simulation modeling with one-third of the papers following this approach.

Of the 30 studies, 16 made projections for the future such as "what if" scenarios quantifying the effects of alternative forest management regimes (e.g., Biber et al., 2020), whereas 12 looked at the present or history, mostly from policy and governance perspectives (Schulz et al., 2022). In contrast, there was only one study that could be classified as a foresight study, deviating significantly from past techno-economic structures (Luhas et al., 2021).

In terms of value chain coverage, most studies (18) focused on both forests and wood (product) markets. There were 3 studies that focused exclusively on markets, while 9 studies focused on forests only.

4.2.3. *Research gaps and policy recommendations emerging from the reviewed literature*

4.2.3.1. Research gaps. Many of the studies implicitly or explicitly pointed to a series of research gaps, revolving around various aspects of the forest bioeconomy, such as policy interactions, biomass availability, environmental impacts, market dynamics, innovation strategies, interdisciplinary perspectives, methods, and data.

Some policy and governance-related studies called for further understanding of the interactions and conflicts (i.e. synergies and trade-offs) between different international, national, and local policies related to bioeconomy strategies (e.g., Hagemann et al., 2016).

Related to the geographical scope of existing research, studies called for more research from both a regional and a local perspective. For example, several studies called for more research on the global perspective and expanding research beyond "Eurocentrism" and focusing also on other regions (e.g., Budzinski et al., 2017; Holmgren et al., 2020; Holz, 2023). Others highlighted the local perspective, pointing to a knowledge gap when it comes to in-depth case studies to understand the effects of bioeconomy strategies at the local level (e.g., Holz, 2023; Korhonen et al., 2021; Sanz-Hernández et al., 2020).

Knowledge gaps related to the uncertainty of future wood availability were highlighted in several studies, and they called for further research on the availability of wood resources and its implications for bioeconomy strategies (e.g., Hagemann et al., 2016; Karan and Hamelin, 2020; Näyhä, 2019; Ollikainen, 2014). Also, related to the availability of raw materials, some studies called for modeling and scenario

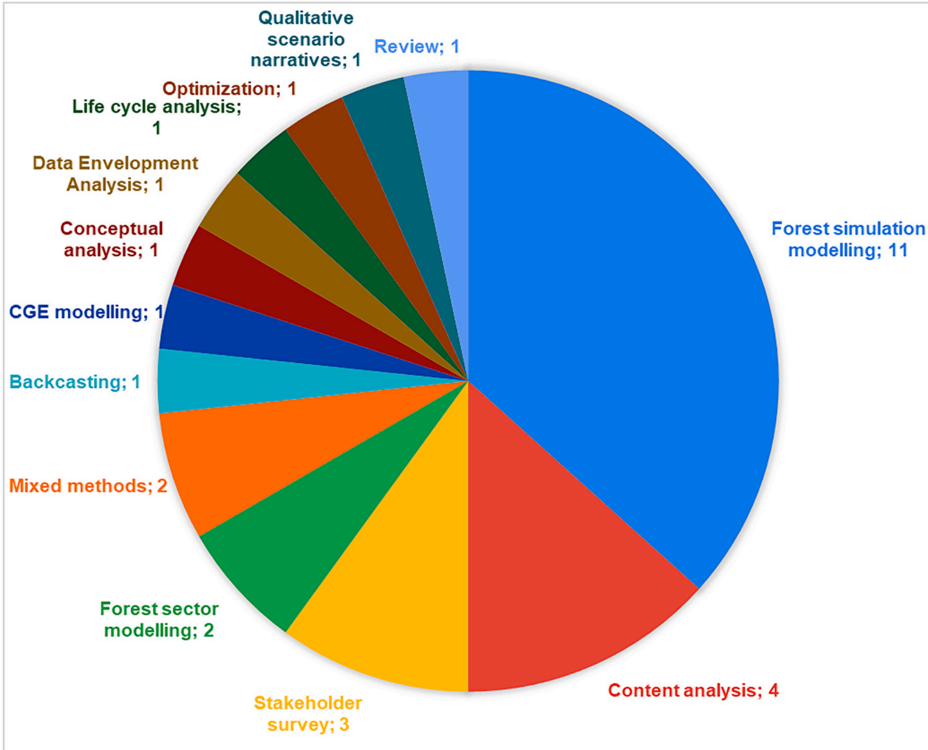

Fig. 7. Methods used in the studies addressing synergies and trade-offs.

comparison i.e., developing systematic modeling tools and explicit scenario comparisons between studies to inform bioeconomy strategies and developments (e.g., Jonsson et al., 2021) or for developing models for non-wood forest products (NWFPs) (e.g., Kurttila et al., 2018). This is especially important when we consider regional differences and perspectives of forest bioeconomy, e.g. the more heavily wood production-orientated Northern Europe versus the relatively more NWFP-orientated Southern Europe. Some studies also called for exploring spatial variations in bioeconomy within regions and considering diverse perspectives from different stakeholders (e.g., Haddad et al., 2019; Lundholm et al., 2020).

Finally, some of the studies focused on consumer perceptions and their willingness to pay, pointing to research gaps related to understanding and measuring the consumers' willingness to pay for bio-based products, especially within and between different EU countries (e.g., Hagemann et al., 2016; Korhonen et al., 2021; Kylkilahti et al., 2020; Toppinen et al., 2018). Similarly, further investigation of the market dynamics and demand for bio-based products was called for (Hassegawa et al., 2022a; Kallio, 2021; Lundholm et al., 2020; Morland and Schier, 2020). Studies also called for improving the accuracy and credibility of substitution assumptions to reduce uncertainty (Hassegawa et al., 2022b; Hurmekoski et al., 2023).

4.2.3.2. Policy recommendations. Few of the studies reflected upon the policy implications of the presented results or explicitly included concrete policy recommendations. Given the broad interdisciplinary character of the literature and the diverse pallet of policy recommendations made in the articles, we grouped the identified policy recommendations into 1st and 2nd generation policy instruments (Table 1). This is a shorthand categorization in political science whereby 1st generation policy instruments (i.e., stick [regulatory], carrot [subsidiary], sermon [communicative], and infrastructure [physical instruments] or concrete management practices) are based on direct, substantive interventions of governments to produce or redistribute certain environmental goods and services (Arts, 2021; Howlett, 2004).

Many of the policy recommendations made in the studies could be categorized as communicative (sermons) in which the main research findings seemed to be aimed at policymakers, but not backed by additional concrete recommendations. The sermons usually included calls for better policy coordination (e.g., Hagemann et al., 2016), integration (Winkel et al., 2022), or awareness raising about the benefits and risks associated with bioeconomy (e.g., Halder et al., 2017). Subsidiary approaches (carrots) were also widely referred to and often included calls for subsidies to substitute fossil fuel-based production inputs with bio-based ones or guaranteed markets for bio-based products (e.g., Biber et al., 2020; Hafner et al., 2020; Halder et al., 2017). Finally, hands-on forest management policy recommendations were common and mostly referred to different management approaches aimed at minimizing trade-offs between timber production and the maintenance of biodiversity (e.g., Bezama et al., 2021; Duncker et al., 2012; Eyvindson et al., 2018).

Second-generation policy instruments refer to the indirect control by governments. Examples are market-based instruments such as forest certification, or payment for ecosystem services (Arts, 2021; Steurer, 2013). Few second-generation instruments could be identified in the literature. Here, studies referred to environmental standardization and labeling or via green public procurement (e.g., Kleinschmit et al., 2014) or payments for ecosystem services (e.g., Winkel et al., 2022).

5. Discussion

5.1. Geographic and disciplinary scope, trade-offs and synergies

While our review focused on forest research in English which explicitly acknowledges the term "bioeconomy" in the title, abstract, or keyword in Europe ($N = 138$), previous bibliometric analyses with less narrow criteria found a slightly larger number of forest bioeconomy publications (e.g., Ilaria et al., 2020; Jankovský et al., 2021).

The reviewed research was published in 62 different journals, but surprisingly some of the popular forest science journals, such as

Table 1
First and second-generation policy instruments are identified in the reviewed literature.

	Instruments	Examples from selected articles
First generation policy instruments	*Sticks*	● Restricting competing raw materials or processes (CO2-tax, building regulations, etc.) (Hafner et al., 2020)
	Carrots	● Subsidiary approaches, that allow regionally tailored bioeconomy solutions (Biber et al., 2020; Hafner et al., 2020) Stimulating wood utilization (e.g., reduction of value-added tax) (Hafner et al., 2020) ● Climate policy instruments setting incentives for substituting fossil fuel-based production inputs for bio-based ones (Hagemann et al., 2016) Subsidies, tax reductions, guaranteed markets (Halder et al., 2017)
	Sermons	● Awareness raising (Halder et al., 2017) ● Evidence-based policymaking (Linser and Lier, 2020) ● Better policy coherence (Eyvindson et al., 2018) Support for R&D, knowledge exchange, and niche creation (Hagemann et al., 2016)
	Infrastructure (Forest Management)	● High management intensity negatively impacts biodiversity attributes leading to trade-offs between maximum volume production and the maintenance of biodiversity at the stand level (Duncker et al., 2012) ● Actively promote biodiversity as part of the management concept (Bezama et al., 2021) ● Diversification of management regimes (Eyvindson et al., 2018)
Second generation policy instruments	*Certification and labelling*	● Environmental standardization and labeling or via green public procurement (Kleinschmit et al., 2014)
	Payments of Ecosystem Services	● Payments for ecosystem services (Winkel et al., 2022) ● Bottom-up participation and learning among ecosystem services innovators (Winkel et al., 2022)

"Canadian Journal of Forest Research," "Forest Science," "International Forestry Review," and "Journal of Forest Economics," published two or fewer of the studies we reviewed. This may again be related to the fact that the term "bioeconomy" is not necessarily used in some of the articles outside the scope of this review, even though they in effect address the topic. Furthermore, limiting the focus of this analysis to the forest or wood bioeconomy may have resulted in a bias towards certain countries, value chains, and market aspects.

The geographical scope of the reviewed studies is extensive in Northern Europe, specifically in Finland, Sweden, and Germany, which aligns with what some previous studies also found (e.g., Holmgren et al., 2020; Ilaria et al., 2020; Jankovský et al., 2021). This geographical focus of Northern Europe is what one could expect if we see forest bioeconomy mainly linked to roundwood production. Germany, Sweden, and Finland are the three biggest roundwood producers in the EU. They were also among the first countries to publish bioeconomy-related policy strategies. Consequently, the results of our review probably reflect more the regional setting of the Nordic and Central European forest sectors, than e.g., Eastern or Southern Europe. Indeed, in the latter countries, the funding for forest-related bioeconomy research has been relatively low (Lovrić et al., 2020). Surprisingly, France being the fourth largest roundwood producer in the EU, was addressed only in three studies, and Poland, the fifth largest roundwood producer in the EU, was not addressed by any of the studies. In general, the results show that there is a clear lack of forest bioeconomy studies with a wider geographical representation of the EU countries, and currently, few countries dominate the field. Given the heterogeneous forest sectors of the EU countries, it would be important to have more studies addressing countries other than the Nordics and central Europe, such as France, Poland, Romania, Slovenia, and Spain.

Interestingly, the discipline findings of the forest bioeconomy literature are somewhat different from what has been found in past forest science studies. Previous studies indicated that ecological sciences are dominant and social sciences are poorly represented in the forest sciences studies (Fouqueray and Frascaria-Lacoste, 2020; Nummelin et al., 2021; Pfau et al., 2014). However, in our literature review, policy and governance, economics and business, and behavioral science studies represent 67% of all the studies reviewed. Moreover, several industrial ecology and innovation studies could also be thought to fall more into social sciences than life science disciplines.

The reviewed studies tended to assess trade-offs more than synergies. However, it should be noted that whether a pair of indicators appear as a synergy rather than as a trade-off depends on the management regimes, societal targets (scenarios), and system boundaries such as time span and region (e.g., Mazziotta et al., 2022). For example, whether wood production and carbon sequestration can be considered a synergy or a trade-off depends on the time span, reference situation, and harvested wood products (HWP) pool emissions and removals and substitution effects (cf. Duncker et al., 2012; Eyvindson et al., 2018). To provide definite policy implications on the existence of synergies and trade-offs, these factors should be controlled by normalizing the framework conditions. However, a detailed meta-analysis was beyond the scope of the current review due to the limited number of observations and the breadth of the approaches and disciplines covered.

Related to the above finding, it is important to point out that forest management studies analyzing synergies and trade-offs at the forest stand level could generate different results compared to studies analyzing the same factors at the landscape or regional level (Bauhus et al., 2017; Duncker et al., 2012). Also, the time scale and other system boundaries used in the study can have important implications; e.g. a trade-off in the short-to-medium run may turn out to be a synergy in the long run (Başkent and Kašpar, 2023). In the studies that seek to provide policy implications, it would be important to acknowledge the potential sensitivity of the results to the spatial scale, time horizon, and other system boundaries analyzed.

Finally, it is interesting to note the study by Ronzon and Sanjuán (2020) who analyzed the synergies and trade-offs between the EU Bioeconomy Strategy and the Sustainable Development Goals. Forest bioeconomy was assessed as a part of the whole bioeconomy, so it has a somewhat different scope than the studies we reviewed above. They found that the Bioeconomy Strategy is aligned with 12 Sustainable Development Goals and synergies predominate over trade-offs in bioeconomy domains (period 1990–2018).

5.2. Remaining research gaps

Various research gaps seem to have received limited attention in the studies we reviewed. For example, adaptation of forests to climate change and the projected increasing future forest disturbances was scarcely analyzed in the literature. Also, the need to study leakage impacts was raised by one study (Haddad et al., 2019). There is evidence that, e.g., synergies and trade-offs between wood production and climate change impacts (Daigneault et al., 2023; Kallio and Solberg, 2018; Päivinen et al., 2022) and wood production and biodiversity impacts (Schier et al., 2022) are affected by the global leakage impacts. However, the previous literature regarding leakage impacts has not yet fully addressed the different aspects related to the issue. For example, leakages have been seen as something to be avoided and causing negative impacts on global emissions and biodiversity, e.g., if wood production moves from the EU to other regions. However, there could also be cases in which leakages lead to fewer emissions, i.e., production moves to more resource-efficient and less emission-intensive countries (Daigneault et al., 2023). For example, in some cases, the same quality products could be manufactured in the southern hemisphere regions with considerably shorter forest rotation times than in the EU. Even with a possible result of increases in the transportation distances to markets (e.g. to the EU markets), the net impacts to greenhouse gases (GHG) emissions could still be beneficial. Thus, there is a need for a more comprehensive analysis of leakage impacts and their role in shaping synergies and trade-offs.

While most of the studies covered both forests and markets, they have a clear emphasis on one or the other. Given the extensive scope of the forest bioeconomy value chain, involving forest management, harvesting, cascading use, logistics, manufacturing, international trade, end products, recycling, etc., the shortage of holistic value chain studies is striking (D'Amato et al., 2020; Ladu et al., 2020; Lovrić et al., 2020). Unbiased policy support on the synergies and trade-offs of the forest bioeconomy requires considering the whole value chain, yet this may not be possible for a single study. From this perspective, it was striking that some studies ventured to give far-reaching policy recommendations, e.g., to EU and national Bioeconomy Strategies, based on the results focused on forest management and generated with one forest simulation model and empirical evidence that represented a region in one country. Thus, more attention ought to be paid to the limitations of their studies concerning policy implications. On the other hand, there appears to be a need for cross-disciplinary research and meta-studies that address the whole forest bioeconomy value chain.

Another limitation of the reviewed studies is that they "only" focus on the forest bioeconomy as a separate value chain of the whole bioeconomy sector. Yet, it is clear that agribioeconomy and forest bioeconomy have important interdependencies when switching or substituting feedstocks, or using the resources of the economy (capital, labor, raw materials), for example. These direct and indirect effects should also be considered, and they may have important implications for how to maximize synergies and minimize trade-offs between forest bioeconomy and the sustainability goals.

5.3. Methodological gaps

A third of the studies explicitly addressing synergies and trade-offs relied on forest simulation modeling. While in the rest of the studies the selection of methods varied from qualitative content analysis (Schulz et al., 2022) to computational general equilibrium modeling (Haddad et al., 2019), the scope of methods applied could be broadened further to cover a larger set of synergies and trade-offs and the factors affecting them.

There are important gaps in existing bioeconomy modeling capacities (Christensen et al., 2022; Verkerk et al., 2021). Whilst models exist that cover certain bioeconomy sectors (e.g., agriculture, forestry, and bioenergy), modeling the emerging forest bioeconomy sectors, such as textiles, chemicals, pharmaceuticals, plastics, and engineered wood products, remains sparse in the context of the forest sector. Furthermore, there is a limited capacity to capture cross-sectoral activities within the bioeconomy transition. Consequently, the current modeling literature tends to focus on single and already existing sectors and does not capture the cross-sectoral links and emerging sectors. Thus, there is a need to integrate modeling efforts and different sectoral expertise which would allow for assessing the synergies and trade-offs that forest bioeconomy development can generate (e.g., Asada et al., 2020). Looking at the methodology from a broader perspective, forest bioeconomy development can either be a transitional or transformational process (Pyka et al., 2022). Transitional development can be understood to be a gradual and sectoral change and process within the current economic and societal structures. Transformational development is a systemic change or process that takes place in new economic structures and lifestyles. Therefore, models that are exclusively based on past data and structures, are not sufficient to capture systemic structural changes - though it is questionable if any model or approach can achieve this. Thus, there is a need for combining various approaches, including qualitative foresight approaches such as backcasting or Delphi (Hurmekoski and Hetemäki, 2013). One promising approach to address the complexities is agent-based models (ABM) or system dynamics (SD) models, representing complex systems analysis - so far hardly used for forest bioeconomy research (Pyka et al., 2022; Yang et al., 2022). In reference to the production possibility frontiers and indifference curves (see section 2), such approaches could essentially be useful for looking into the dynamics of stakeholder preferences (demand side), in addition to the techno-economic potentials of providing ecosystem services (supply side).

5.4. Policy implications and the way forward

The studies we reviewed draw policy implications with important insights. However, most policy recommendations identified in the literature fall into the "sermon" (communication) category, i.e., formulated in generic terms, in which information or messages are communicated to target audiences that are not clearly defined, and when the recommendations are not necessarily backed by tangible policy actions. This could be attributed to the fact that many studies reviewed herein are theory-informed policy studies. Whereas these studies may be able to postulate policy processes, they do not necessarily offer a clear way to guide action. However, practitioner audiences desire accurate descriptions of policymaking and actionable take-home messages (Cairney, 2023). Nevertheless, policy research is about reducing ambiguity, i.e., reducing the number of competing interpretations of a problem (Ibid.).

There is still room for improvement in providing the policy implications for bioeconomy. First, it is important not to extend the policy implications to areas or substances for which the research itself does not provide results. For example, studies focusing only on forest management in one local region can hardly have the competence to provide policy implications for the whole forest bioeconomy value chain or bioeconomy strategies at the EU or even national level, or vice versa. Effective policy measures should not be narrowly placed, as this may cause side effects like market distortion. We thus need more interdisciplinary synthesis studies based on existing scientific knowledge and written and communicated in a format that policymakers or their advisers can grasp, such as the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) processes.

Maximizing synergies and minimizing trade-offs between forest bioeconomy and climate change mitigation and forest ecosystem services remain important endeavors for the future.

To this end, research needs to address several complex issues simultaneously, such as the whole value chain from forests to markets and ecological, economic, and social sustainability perspectives. Therefore, the contribution of many disciplines and integrative modeling and foresight approaches are needed. For example, related to the synergies and tradeoffs between the SDGs and forests, Timko et al. (2018) call for coherence among policy clusters that directly affect or are impacted by forests (e.g., ecosystem services and livelihoods, bioeconomy or justice, equality, and inclusion). Today, bioeconomy policy serves as a conceptual umbrella for several already existing policies with little tangible effect (Töller et al., 2021). It can therefore be understood as an emerging policy field backed by scarce bioeconomy-specific instruments (Ibid.). As an example of this conundrum, in most of the studies that extended the coverage to both forestry and markets, the market aspect received very little emphasis, so the trade-offs focused on the provision of ecosystem services by forests and excluded the analysis of changes in societal demands or market conditions. This can result in too simplistic policy advice. For example, a common measure for climate change adaptation is to prefer mixed species forests over monocultures. However, what remains unknown is the extent to which wood-processing industries and forest owners can adapt to such change and what is the value of standing forests given different supply and demand conditions.

This review indicates that we do not need only more research on certain topics and methods highlighted earlier, but also more projects and facilitators that help to synthesize the existing research on forest bioeconomy. The EU Research, Development and Innovation framework programs are one potential tool for these. However, they need to emphasize more the interdisciplinary and the whole forest bioeconomy value chain projects than currently done. In addition, such projects, platforms, and funding are also required at the national level.

Given the complex setting of policymaking, one essential part of science policy work needs to be communication and science policy and science-media dialogue (Hetemäki, 2019). Bioeconomy remains a difficult concept to communicate for several reasons i.e., differing conceptualizations and worldviews, competing discourses, and due to several knowledge gaps in the communication process (i.e., who communicates and to whom it should be communicated) (Giurca, 2023). The aim must ultimately be to distribute knowledge and engage scientists, policymakers, the media, and the problem's associated stakeholders and experts in joint interpretation and sense-making of various types of evidence and perspectives and identify new open research questions (Hetemäki, 2019).

6. Conclusions

Based on our results, there have been very few studies explicitly analyzing synergies and trade-offs, which generally focus on wood production versus climate change mitigation, biodiversity, and other ecosystem services. This paucity could be due to the difficulty of operationalizing the concept of synergies and trade-offs in different disciplines, as well as due to methodological and empirical challenges to measure synergies and trade-offs. It should also be noted that our review focused on studies dealing with the forest bioeconomy, while there is a wider and well-established body of literature addressing synergies and trade-offs in forests that do not explicitly mention the concept of bioeconomy. More evidence-based information is needed to inform forest management and governance.

In addressing synergies and trade-offs, we recommend that research should acknowledge the following dimensions:

- Coverage of disciplines and the forest bioeconomy value chain.
- Temporal (especially long-term) and spatial scale (forest stand vs. landscape, wood-based vs. other sectors, country vs. global) of interventions, and consequent synergies and trade-offs.
- Integrating the adaptation to changing climate and leakages to the analysis of synergies and trade-offs.
- Integrated and systemic quantitative modeling approaches to better capture the cross-sectoral impacts and more holistically analyze the synergies and trade-offs.
- For issues that cannot be captured purely based on quantitative models, qualitative foresight approaches are needed.

This review highlights the importance of combining existing research from different fields in addition to conducting new research. This is crucial, because decision makers often struggle not because of a lack of scientific information, but because of a shortage of synthesis studies that are written in a clear and understandable format, and that can help them plan policies effectively.

Author statement

All authors state that they contributed to the article and agree with the final submission. Furthermore, we confirm that no part of it has been published elsewhere, nor is under consideration by any other publication.

Declaration of generative AI in scientific writing

"ChatGPT" was used for scoping the study before starting to write the manuscript (not for actual analysis or the text in the manuscript). "Grammarly" (https://app.grammarly.com/) was used for a grammar, spelling, and stylistic check of the whole manuscript. Most of the corrections and suggestions for stylistic improvement made by this tool were accepted.

CRediT authorship contribution statement

L. Hetemäki: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **D. D'Amato:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **A. Giurca:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **E. Hurmekoski:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

The idea for the study was initiated and the work was financially supported by the European Forest Institute (EFI), we gratefully acknowledge this support. Any opinion, finding, conclusion or recommendation expressed in this material is that of the authors and the EFI does not accept any liability in this regard.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2024.103204.

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